

A Test of Time Reversal Invariance in Stopped Kaon Decay $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$

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for the KEK -- E246 collaboration

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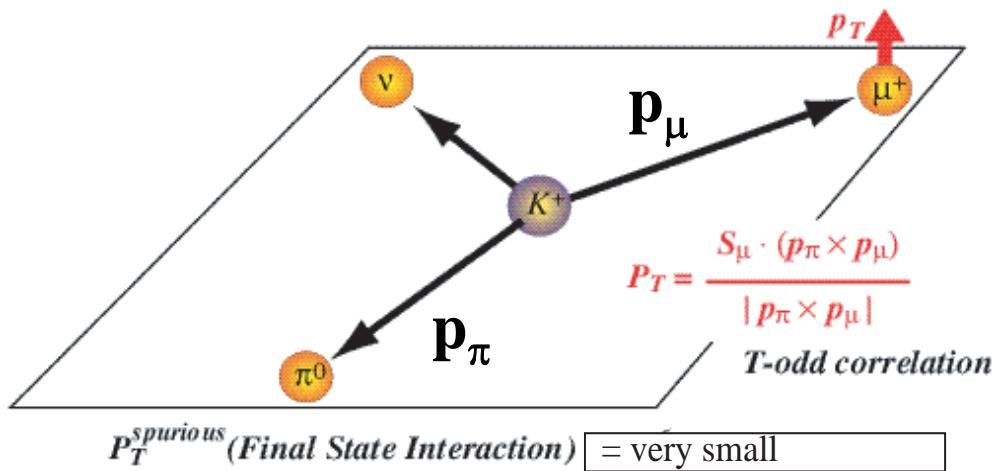
Santa Fe, NM

- Introduction and Theory
- Experimental details
- Analysis method
- Final results for the entire data set
- J-PARC proposal

E246 collaboration

- | | |
|---------------|--|
| Japan | • KEK • Univ. of Tsukuba,
• Tokyo Institute of Technology
• Univ. of Tokyo • Osaka Univ. |
| Russia | • Institute for Nuclear Research -- Moscow |
| Canada | • TRIUMF • Univ. of British Columbia
• Univ. of Saskatchewan • Univ. of Montreal |
| Korea | • Yonsei Univ. • Korea Univ. |
| U.S.A. | • Virginia Polytech Institute • Princeton Univ. |
| Taiwan | • National Taiwan Univ. |

Transverse Muon Polarization in $K^+ \rightarrow \pi^0 \mu^+ \nu$



Triple product correlation
--changes sign under T_{op}

$P_T \neq 0 \rightarrow T\text{-violation}$

$K_{\mu 3}$ decay form factors and T violation

$$M \propto f_+(q^2) [2 \tilde{p}_K^\lambda \bar{u}_\mu \gamma_\lambda (1 - \gamma_5) u_\nu + (\xi(q^2) - 1) m_\mu \bar{u}_\mu (1 - \gamma_5) u_\nu]$$

$$\rightarrow \xi(q^2) = f_-(q^2) / f_+(q^2)$$

$$P_T \sim \text{Im}(\xi) \frac{m_\mu}{m_K} \frac{|p_\mu|}{E_\mu + |p_\mu| n_\mu \cdot n_\nu - m_\mu^2 / m_K}$$

$\text{Im}(\xi) \neq 0 \longleftrightarrow T\text{-violation}$

Model predictions for P_T

Model	$K^+ \rightarrow \pi^0 \mu^+ \nu$	$K^+ \rightarrow \mu^+ \nu \gamma$
■ Standard Model	$< 10^{-7}$	$< 10^{-7}$
■ Final State Interactions	$< 10^{-5}$	$< 10^{-3}$
■ Multi-Higgs	$\leq 10^{-3}$ $P_T(K^+ \rightarrow \pi^0 \mu^+ \nu) \approx 3 P_T(K^+ \rightarrow \mu^+ \nu \gamma)$	$\leq 10^{-3}$
■ SUSY with squarks mixing	$\leq 10^{-3}$ $P_T(K^+ \rightarrow \pi^0 \mu^+ \nu) \approx -3 P_T(K^+ \rightarrow \mu^+ \nu \gamma)$	$\leq 10^{-3}$
■ SUSY with <i>R</i> -parity breaking	$\leq 4 \times 10^{-4}$	$\leq 3 \times 10^{-4}$
■ Leptoquark model	$\leq 10^{-2}$	$\leq 5 \times 10^{-3}$
■ Left-Right symmetric model	0	$< 7 \times 10^{-3}$

- $P_T(K \rightarrow \pi \mu \nu)$ and $P_T(K \rightarrow \mu \nu \gamma)$ are complementary.

KEK E246 experiment

Features

- Stopped K^+ experiment with a SC toroidal spectrometer
- Measurement of all decay kinematic directions
 - Double ratio measurement with small systematic errors

History

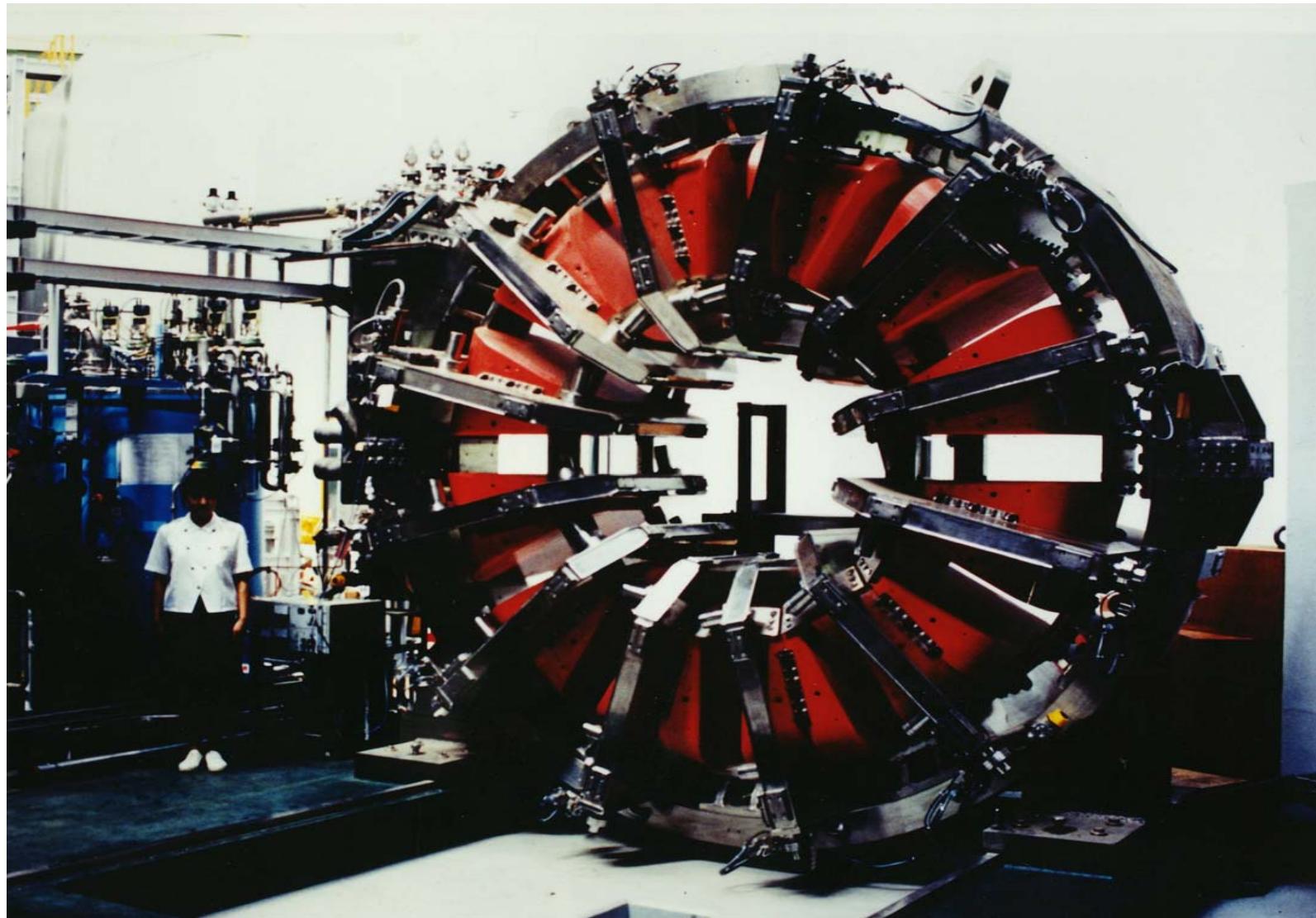
- **1992-1995** : detector construction
- **1999** : first result ($\sim 1/3$ of data) [Phys.Rev.Lett. **83** (1999) 4253]
 $P_T = -0.0040 \pm 0.0040(\text{stat}) \pm 0.0010(\text{syst})$
 $\text{Im}\xi = -0.0230 \pm 0.0070(\text{stat}) \pm 0.0030(\text{syst})$
- **2004** : final result (11.8×10^6 events) [Phys.Rev.Lett. **93** (2004) 131601]
 $P_T = -0.0017 \pm 0.0023(\text{stat}) \pm 0.0011(\text{syst}) < 0.005 \text{ (90\% CL)}$
 $\text{Im}\xi = -0.0053 \pm 0.0071(\text{stat}) \pm 0.0036(\text{syst}) < 0.016 \text{ (90\% CL)}$

Other Physics Result

- $K^+ \rightarrow \mu^+ \nu \gamma$: $P_T = -0.0064 \pm 0.0185(\text{stat}) \pm 0.0010(\text{syst})$

[V.Anisimovsky et al., Phys.Lett. B562 (2003) 166]

Superconducting toroidal magnet

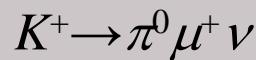
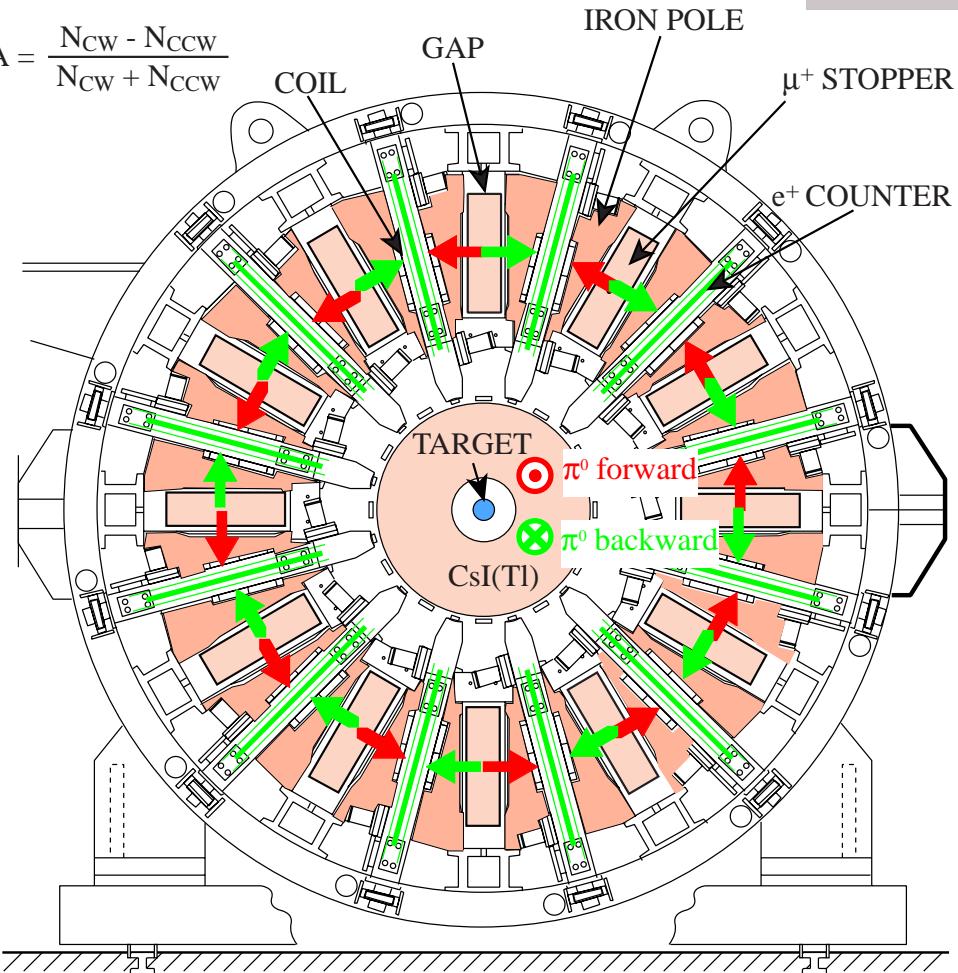


E246 experimental setup

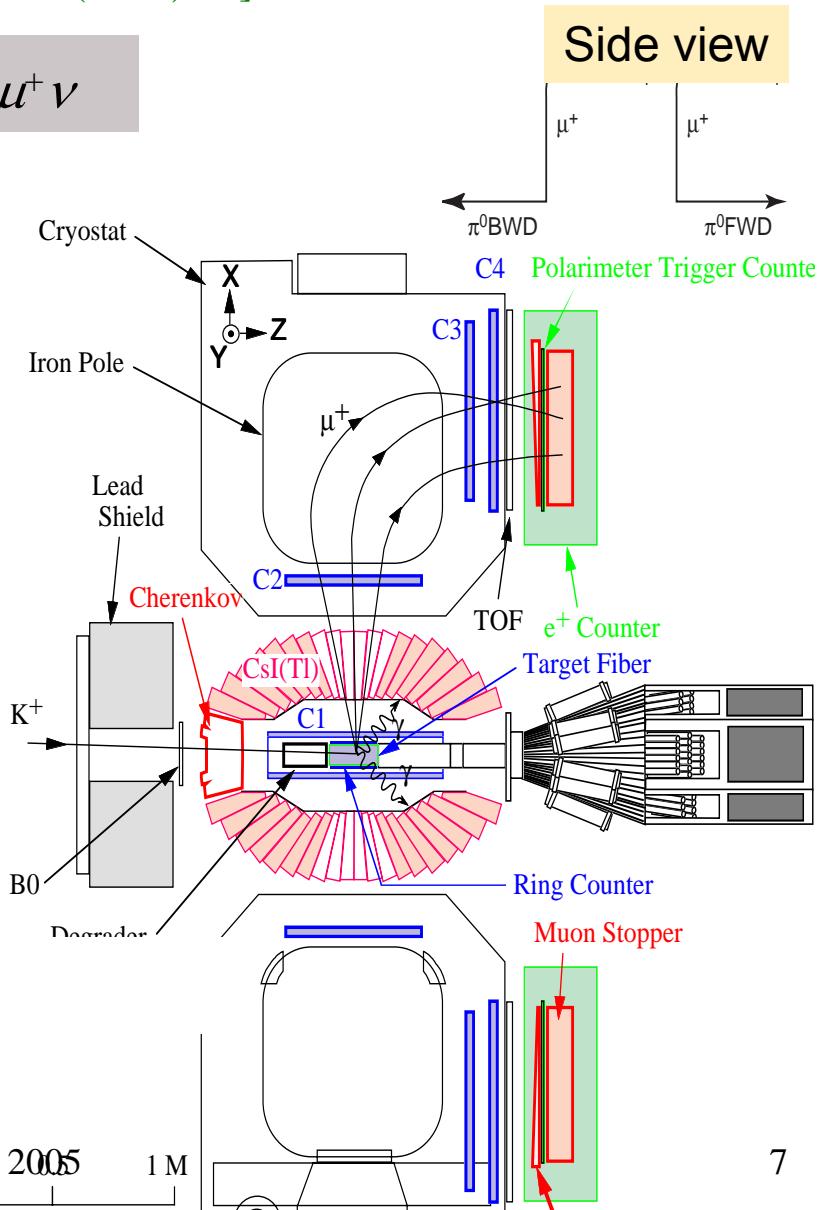
[J.Macdonald *et al.*; NIM A506 (2003) 60]

End view

$$A = \frac{N_{CW} - N_{CCW}}{N_{CW} + N_{CCW}}$$

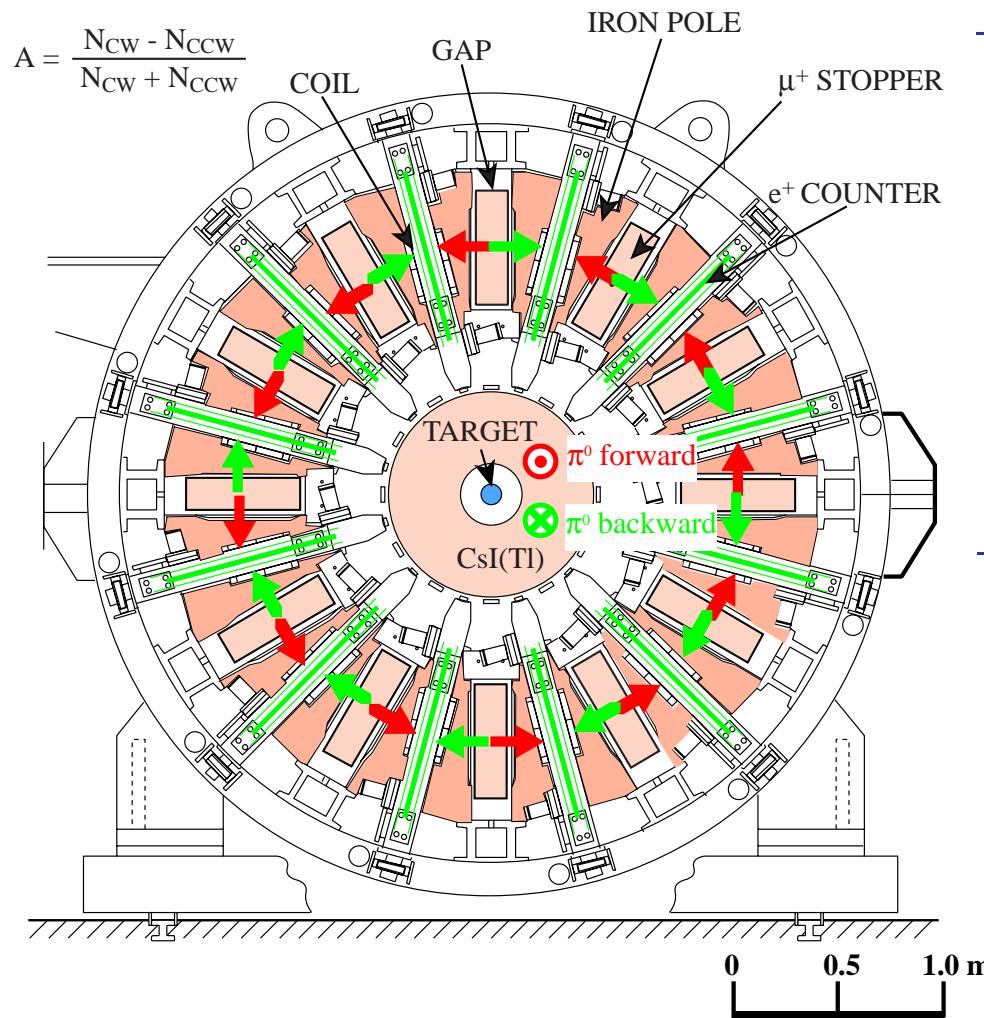


Side view



Determination of P_T

Stopped K^+ beam



Symmetrical detector system

**CW counter of one sector =
CCW counter of the adjacent sector**

$$R = \frac{\sum_{i=1}^{12} N_{CW}^i}{\sum_{i=1}^{12} N_{CCW}^i} = 1 + 2A$$

**Efficiencies of the positron counters
are cancelled out.**

Double ratio measurement

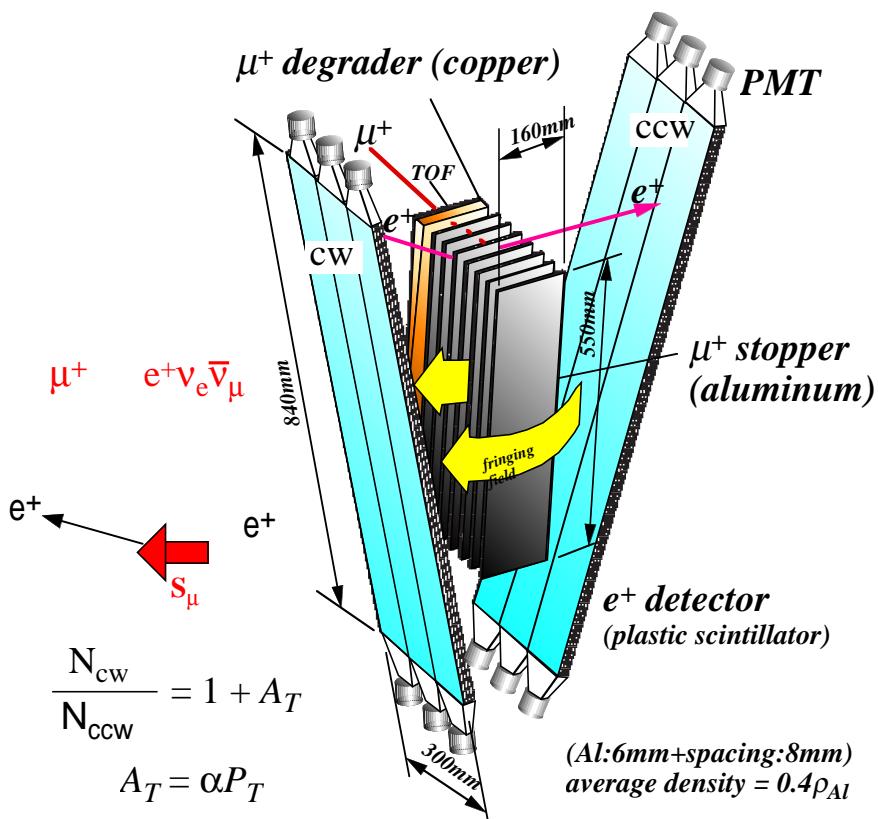
$P_T(\pi^0 \text{ forward}) \text{ & } P_T(\pi^0 \text{ backward})$

$$A_T = \left(\frac{R_{fwd}}{R_{bwd}} - 1 \right) \times \frac{1}{4}$$

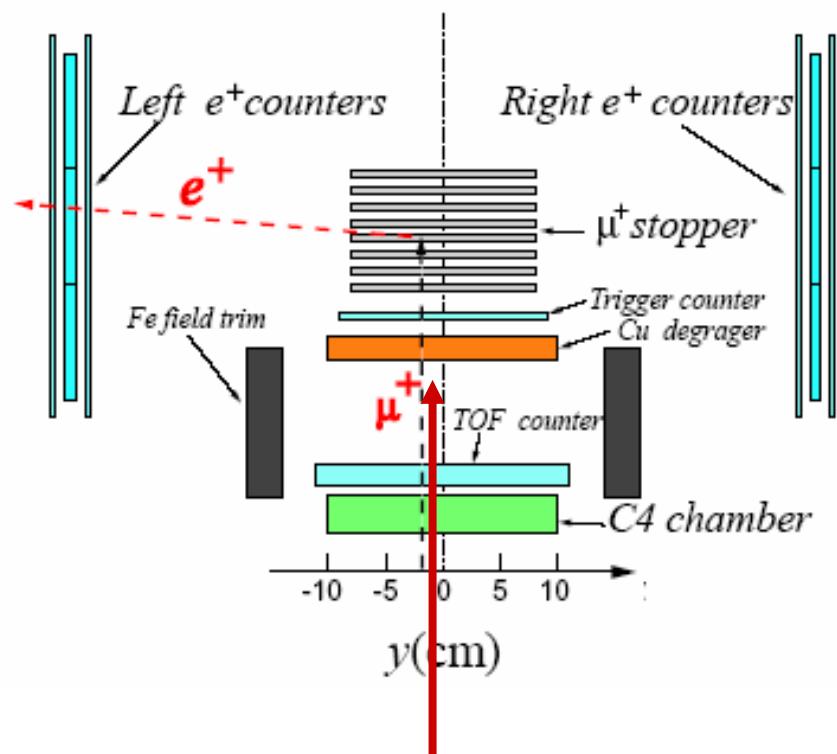
**P_N contribution to systematic error is
drastically reduced.**

Muon polarimeter

One-sector view

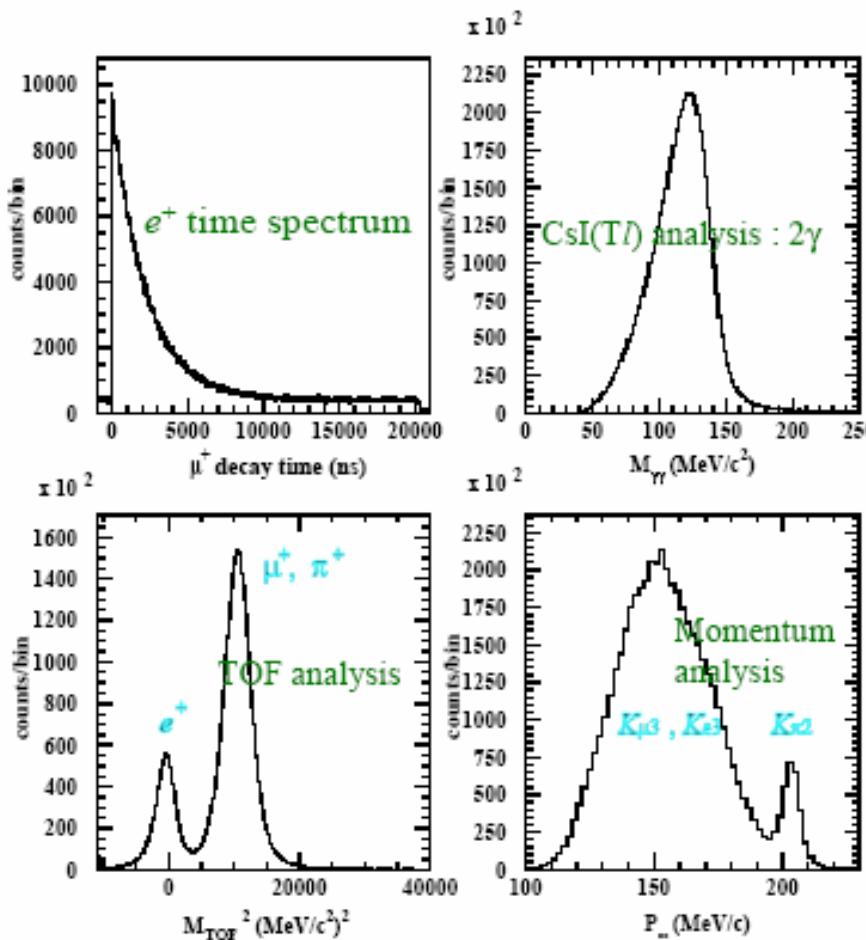


Cross section

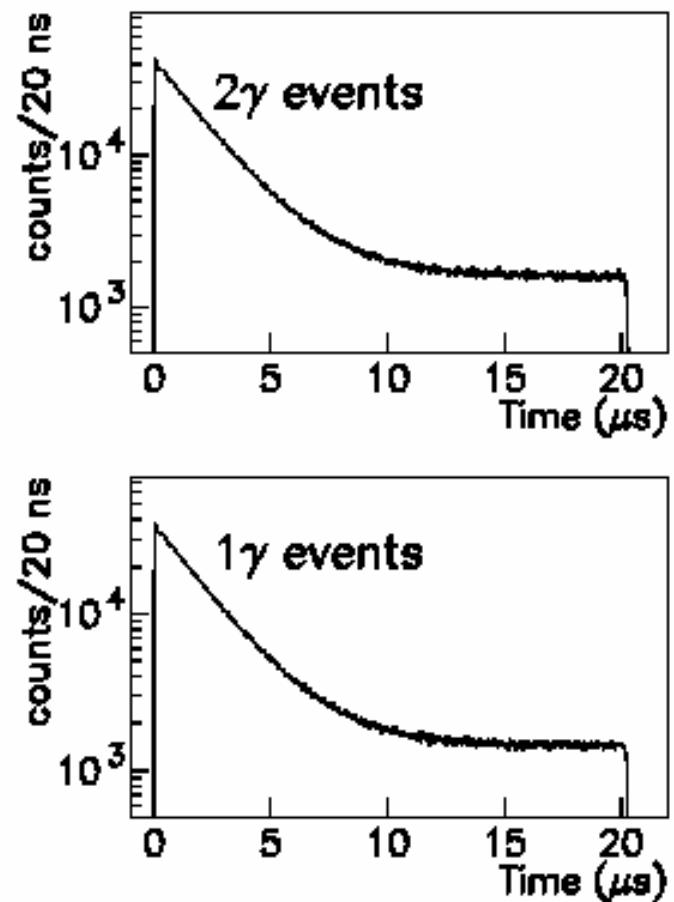


Experimental data

$K^+ \mu_3$ event selection



e^+ time spectra



Final Result

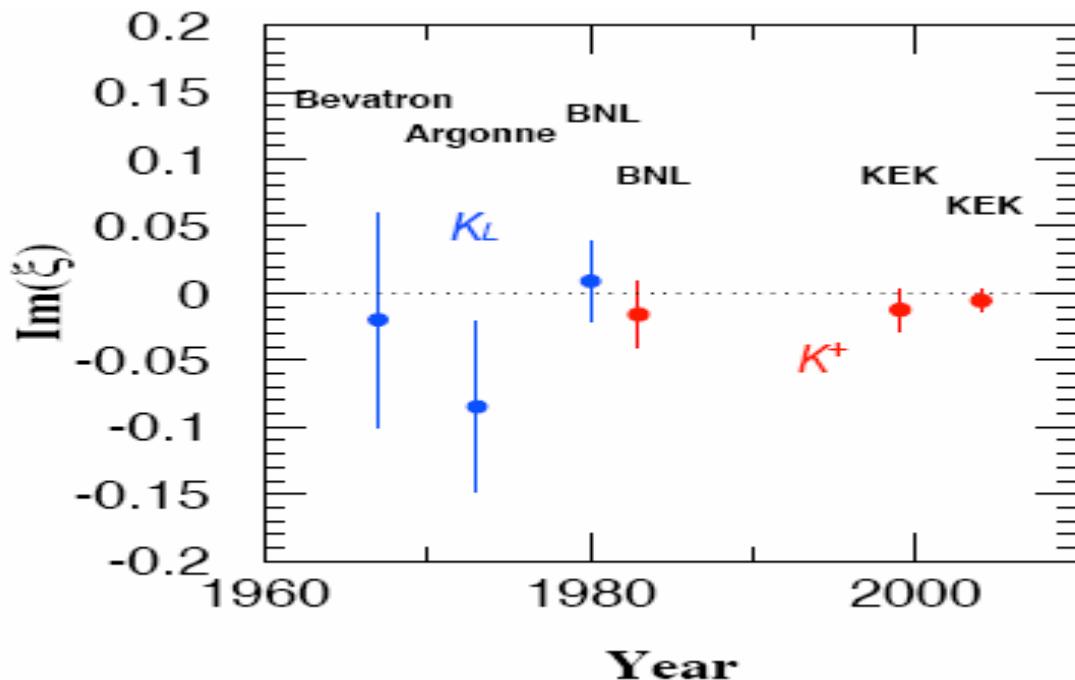
$$P_T = -0.0017 \pm 0.0023(\text{stat}) \pm 0.0011(\text{syst})$$

($|P_T| < 0.0050$: 90% C.L.)

$$\text{Im}\xi = -0.0053 \pm 0.0071(\text{stat}) \pm 0.0036(\text{syst})$$

($|\text{Im}\xi| < 0.016$: 90% C.L.)

Limited by Statistics



Backgrounds—
--accidentals 5-10%
-- $K \rightarrow \pi^+\pi^0$ 5-10%

Systematic errors

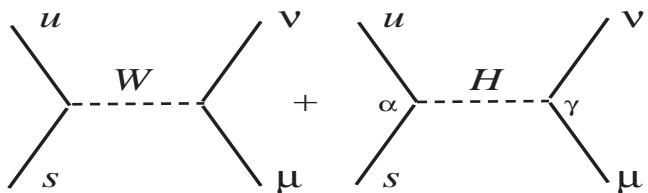
- Sum 12 gaps : 12-fold rotational cancellation
- fwd/bwd : π^0 forward/backward cancellation

Source of Error	$\Sigma 12$	fwd/bwd	$\delta P_T \times 10^4$
e^+ counter r-rotation	o	o	0.5
e^+ counter z-rotation	o	o	0.2
e^+ counter ϕ -offset	x	o	2.8
e^+ counter r-offset	o	o	<0.1
e^+ counter z-offset	o	o	<0.1
μ^+ counter y-offset	x	o	<0.1
MWPC ϕ -offset (C4)	x	o	2.0
CsI misalignment	o	o	1.6
B offset (ε)	x	o	3.0
B rotation (δ_x)	x	o	0.4
B rotation (δ_z)	x	x	5.3 ←
K^+ stopping distribution	o	o	<3.0
μ^+ multiple scattering	x	x	7.1 ←
Decay plane rotation (θ_r)	x	o	1.2
Decay plane rotation (θ_z)	x	x	0.7
$K_{\pi 2}$ DIF background	x	o	0.6
K^+ DIF background	o	x	< 1.9
Analysis	-	-	3.8
Total Systematic Error			11.4

Model implications

Three Higgs doublet model

$$L = (2\sqrt{2}G_F)^{1/2} \sum [\alpha_i U_L K M_D D_R + \beta_i U_R M_U K D_L + \gamma_i N_L M_E E_R] H_i^+ + h.c.$$



$$\begin{aligned} \text{Im}\xi &= \text{Im}(\alpha_1 \beta_1^*) \times (v_2/v_3)^2 \times (m_K/m_{H^+})^2 \\ &= \text{Im}(\alpha_1 \gamma_1^*) \times (m_K/m_{H^+})^2 \end{aligned}$$

v_i : vacuum expectation values

$\alpha_i, \beta_i, \gamma_i$: mixing matrix elements

- $|\text{Im}\xi| < 0.016$ (90% C.L.) $\Rightarrow \text{Im}(\alpha_1 \gamma_1^*) < 544$ (at $m_H = m_Z$)
cf. $\text{BR}(B \rightarrow X \tau \bar{\nu}_\tau) \Rightarrow \text{Im}(\alpha_1 \gamma_1^*) < 1900$ (at $m_H = m_Z$)

Neutron EDM in 3HD model

$$d_n \approx 4/3 \quad d_d \approx \text{Im}(\alpha_1 \beta_1^*) \times m_d / m_H^2$$

$$v_2/v_3 \approx m_t/m_\tau \approx 100 \quad [\text{R.Garisto and G.Kane, Phys. Rev. D44 (1991)2789}]$$

- $|\text{Im}\xi| < 0.016$ (90% C.L.) $\Rightarrow d_n < 7 \times 10^{-27} e \text{ cm}$
cf. $d_n^{\text{exp}} < 3.1 \times 10^{-26} e \text{ cm}$ (2005)

Necessary Improvements for J-PARC T-Violation Experiment

- Higher K^+ Beam Intensity
- Improved K/π ratio
- Improved vertex determination
- Better determination of the muon stopping position → active polarimeter

J-PARC T violation experiment

- Methodology :
 - Stopped K^+ method rather than an in-flight decay experiment
 - Double ratio measurement in the decay kinematic space
 - Longitudinal field on the P_T component
- Desirable detector :
 - Larger $K_{\mu 3}$ acceptance than E246
 - Simultaneous P_T measurement of $K_{\mu 3}$ and $K_{\mu\nu\gamma}$
 - Smaller instrumental systematic errors (in B_z and θ_z)
- Sensitivity goal :
 - J-PARC experiment :

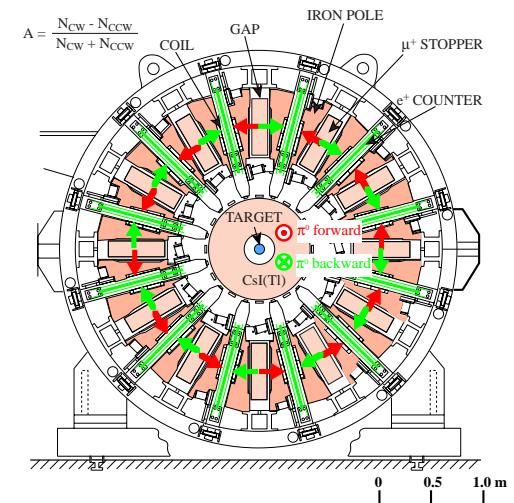
$$\delta P_T^{syst}(\text{JPARC}) \sim 1/10 \quad \delta P_T^{syst}(\text{E246}) \sim 10^{-4}$$

$$\delta P_T^{stat}(\text{JPARC}) \sim \delta P_T^{syst}(\text{JPARC}) \sim 10^{-4}$$

Strategy

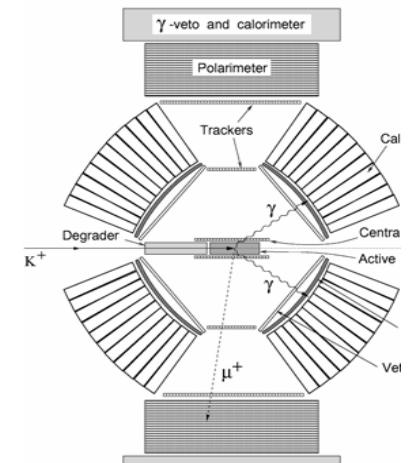
■ Upgraded E246 detector in Phase 1

- E246 was statistics limited
- well known detector systematics
- beam intensity in Phase 1 is limited
- several improvements in detector elements
 - Active muon stopper
 - Magnet to control muon spin



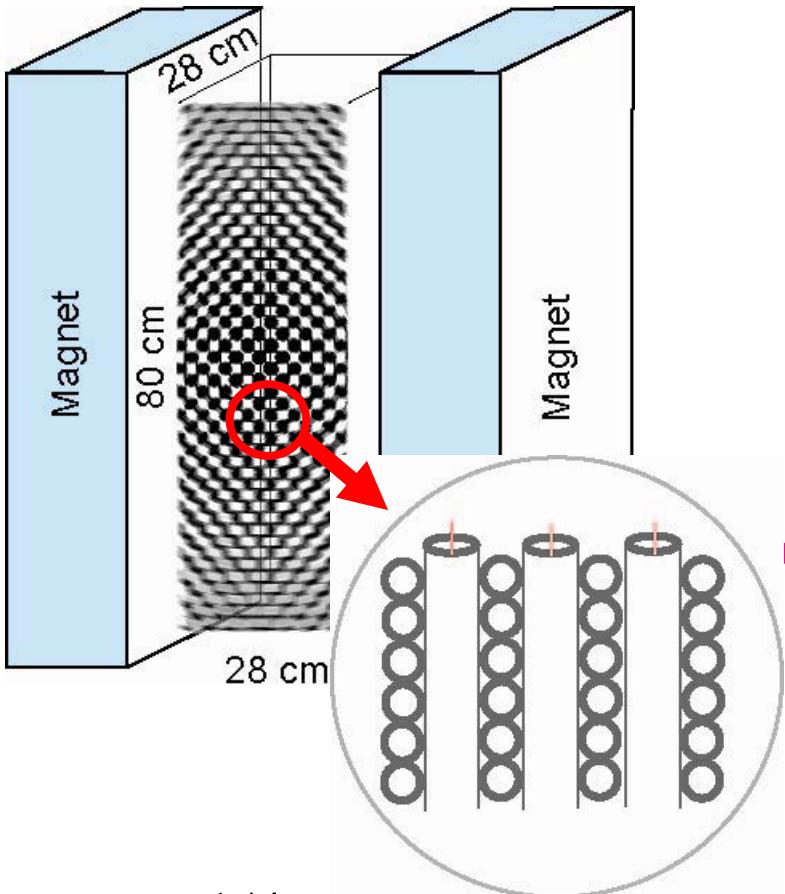
■ Phase 2 experiment with the highest sensitivity

- completely new detector
- π^0 detection based on a new concept
- utilize the highest beam intensity of $\sim 10^7/\text{s}$
- optimization of detector acceptance -- for both $K_{\mu 3}$ and $K_{\mu \nu \gamma}$



Phase1: Upgraded E246 setup

Active polarimeter and Magnet to control muon spin



$$\bullet \rho_{eff} \sim 1/4 \rho_{Al}$$

- Measurement of
 - μ^+ decay vertex
 - e^+ energy and angle

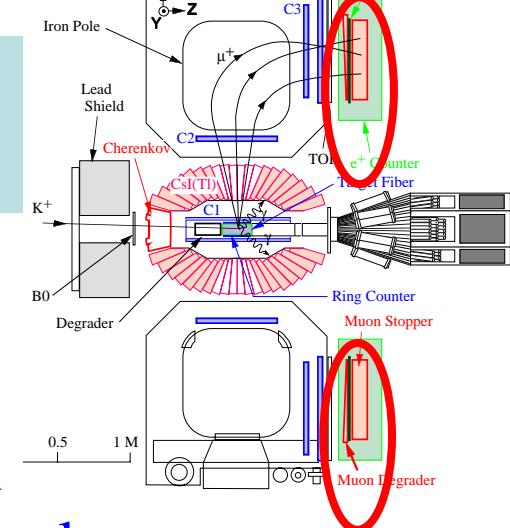
**Good resolution for radial direction
but not for axial direction:-**

- ∴ *Two orientations are necessary*
- Analysis

$$W(E_e, \theta) = 1 + P\alpha(E_e) \cos \theta_e.$$

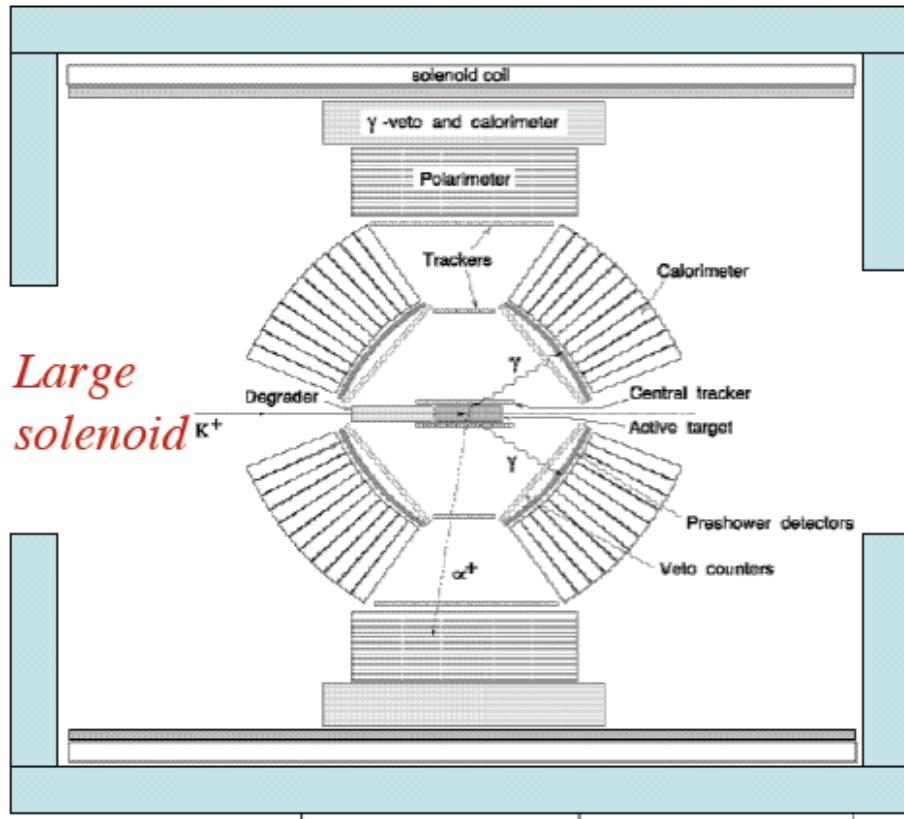
$$P^k = \int_0^{E_e^{max}} \frac{\langle \cos \theta_e^k \rangle_E}{\alpha(E_e)} w(E_e) dE_e$$

Highest analyzing power



An Option with Magnetic Field

- Unified field for polarimeter and tracking by a large solenoid



- Decoupling of muon spin from stray fields
- Charged particle tracking for better decay mode I.D.

- Field distribution with high precision required

Field parameters

- Strength : 1-3 kG
- Alignment+symmetry : 10^{-4}
- Allowed stray field : 100 mG

- Field alignment with 10^{-4} : how feasible is it?

Expected $K_{\mu 3}$ sensitivity

	New detector	E246 upgrade	E246(KEK)
K^+ beam intensity	$10^7/s$ (Phase 2)	$10^6/s$	$10^5/s$
K^+ stopping efficiency	0.30	0.40	0.40
Net runtime	10^7 s	10^7 s	1.5×10^7 s
Acceptance	2.0×10^{-4}	3.8×10^{-4}	5.5×10^{-5}
Number of decays	2.0×10^{10}	1.5×10^9	3.3×10^7
fwd/bwd events	1.3×10^{10}	5.0×10^8	1.1×10^7
Analyzing power	0.3	0.27	0.27
P_T kinematic atten	0.8	1.0	~ 0.70
δP_T $K_{\mu 3}$	4×10^{-5}	1.13×10^{-4}	2.3×10^{-3}
δP_T $K_{\mu\nu\gamma}$	7×10^{-5}	-	-

Detailed Proposal will be submitted – March 2006.

Summary & Outlook

- Transverse muon polarization in $K^+ \rightarrow \pi^0 \mu^+ \nu$ decay is a good probe of CP violation beyond the standard model.
- The final result of our KEK-E246 experiment shows no evidence for T violation with $\text{Im}\xi = -0.0053 \pm 0.0071(\text{stat}) \pm 0.0036(\text{syst})$, or $|\text{Im}\xi| < 0.016$ (90% C.L.). This is a factor of 3 better than the previous BNL K^+ experiment but it is statistically limited.
- This limit constrains the parameters of some non-standard CP violation models with high sensitivity.
- Our proposed next generation P_T experiment at J-PARC will allow us to reduce this limit by more than a factor of 10.

New Collaborators are Very Welcome !!

Other T violation studies

1. $K^0 - \bar{K}^0$ system

- CPLEAR first direct observation of
 $K^0 \rightarrow \bar{K}^0$ vs. $\bar{K}^0 \rightarrow K^0$ asymmetry (0.66 ± 0.13)% ; 1998
- KTeV observation of CP-odd & T-odd asymmetry in
 $K_L^0 \rightarrow \pi^+ \pi^- e^+ e^-$ (13.6 ± 2.3 (stat) ± 1.2 (syst))% ; 1999

2. Other systems : up to now only upper limits

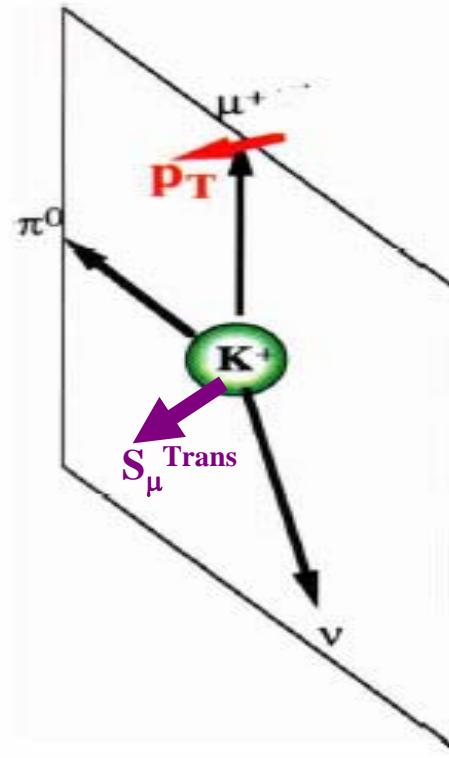
- Neutron EDM (P and T violation) $|d_n| < 0.31 \times 10^{-25}$ e cm ; 2005
- Nuclear beta decay (R -parameters) $R = (0.9 \pm 2.2) \times 10^{-3}$; 2003
- Muon decay (e^+ polarization P_{T2}) $\langle P_{T2} \rangle = (-3.7 \pm 7.7 \pm 3.4) \times 10^{-3}$; 2005

3. B meson system : theoretical suggestions

- $P_T (B \rightarrow D\tau\nu), B \rightarrow VV, B \rightarrow K^* l^+ l^-, etc.$

Extra slides

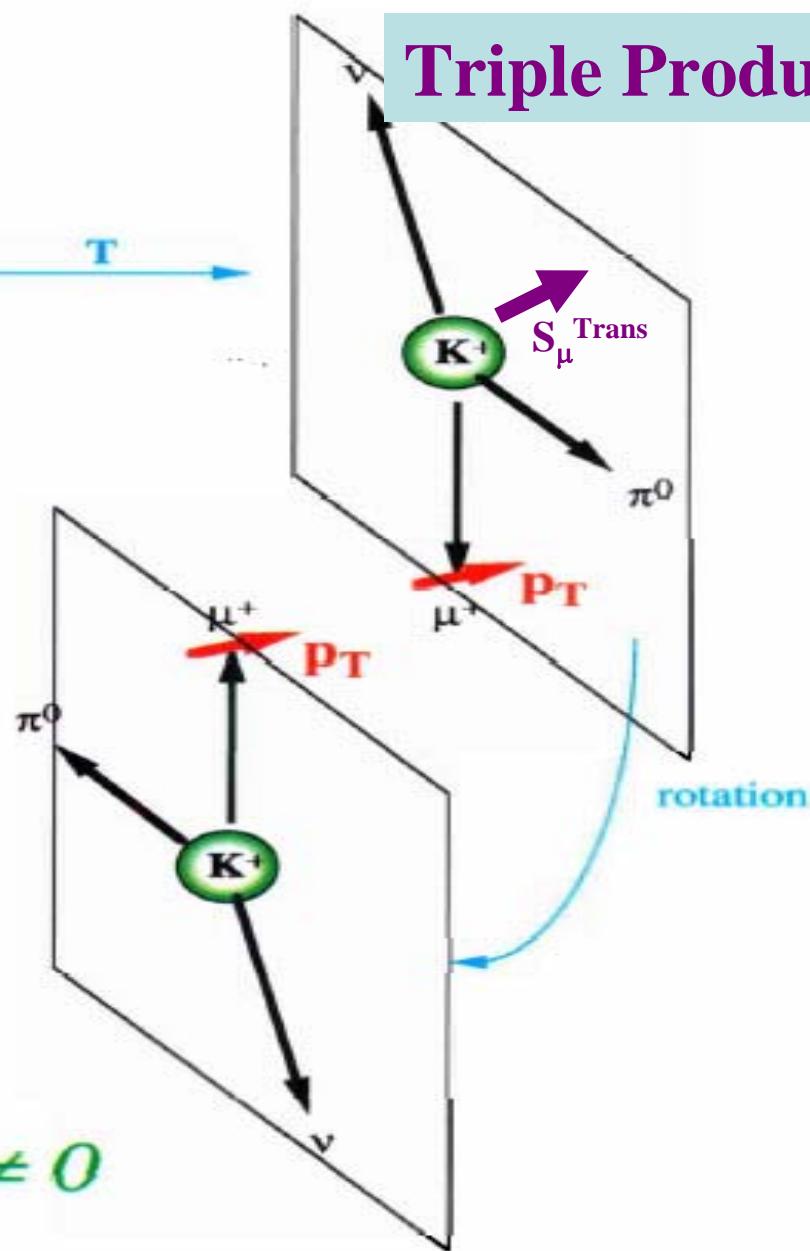
Triple Product Correlation



$$P_T = \frac{\vec{s}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)}{|\vec{p}_\pi \times \vec{p}_\mu|}$$

T violation

$$\Leftrightarrow P_T \neq 0$$

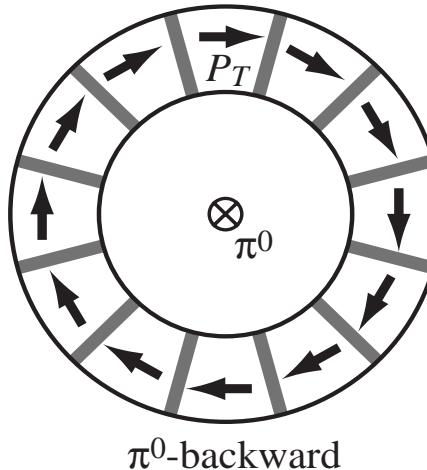
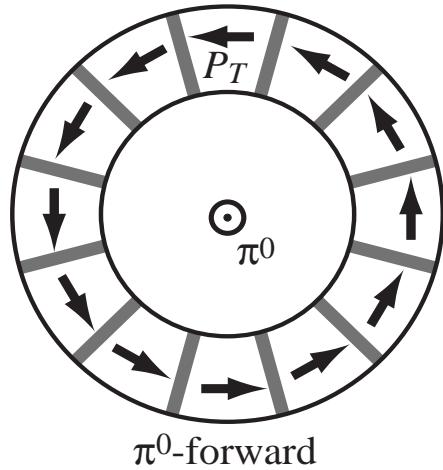


Double ratio measurement

$$\frac{\left[\sum_{i=1}^{12} N_i(cw) / \sum_{i=1}^{12} N_i(ccw) \right]_{fwd-\pi^0}}{\left[\sum_{i=1}^{12} N_i(cw) / \sum_{i=1}^{12} N_i(ccw) \right]_{bwd-\pi^0}} = 1 + 4\alpha <\cos\theta_{P_T}> P_T$$

i : sequential number of magnet gaps(1..12)

α : analyzing power

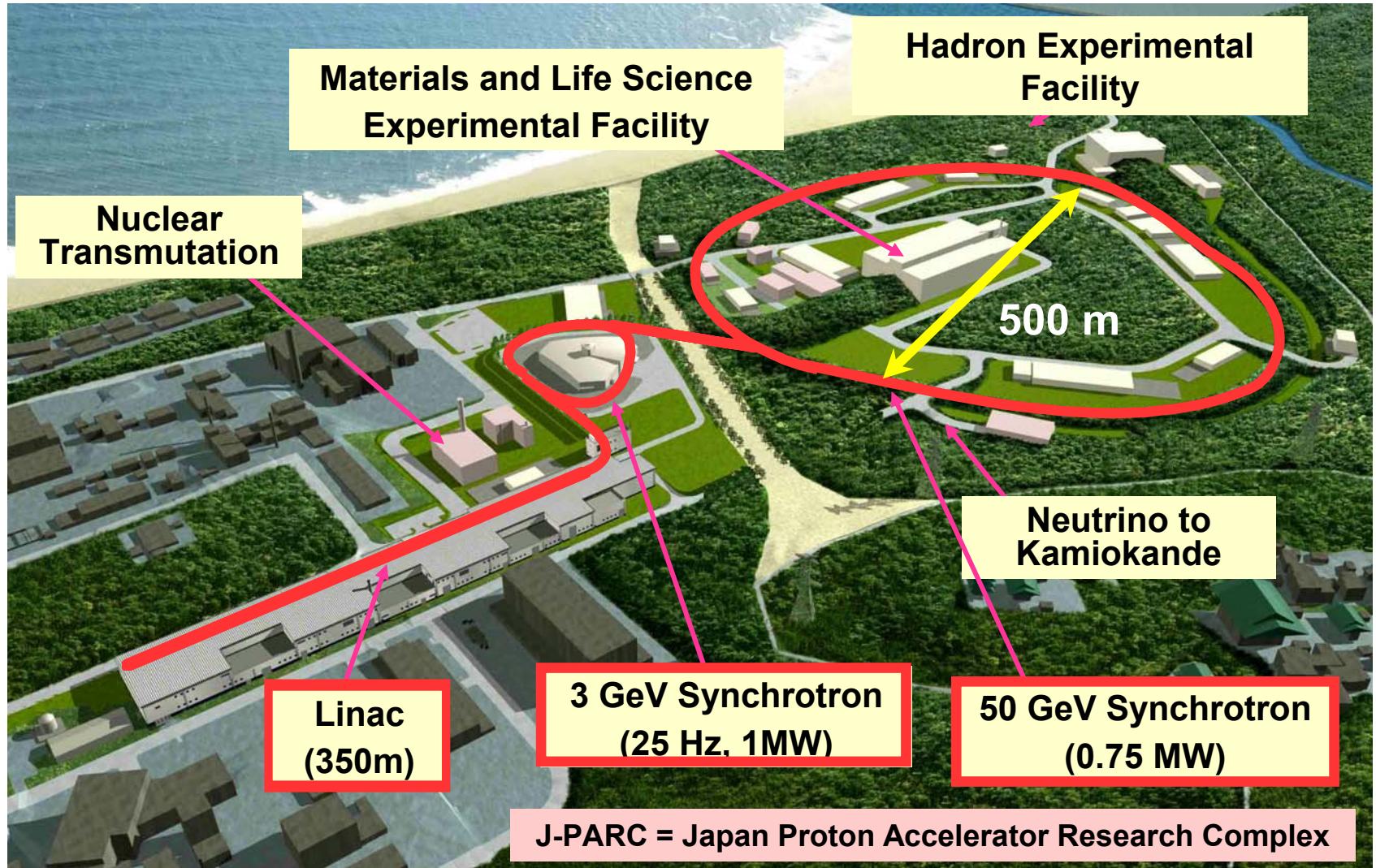


**Counter(i) is CW cter
for gap (i) but CCW
cter for gap (i-1).**

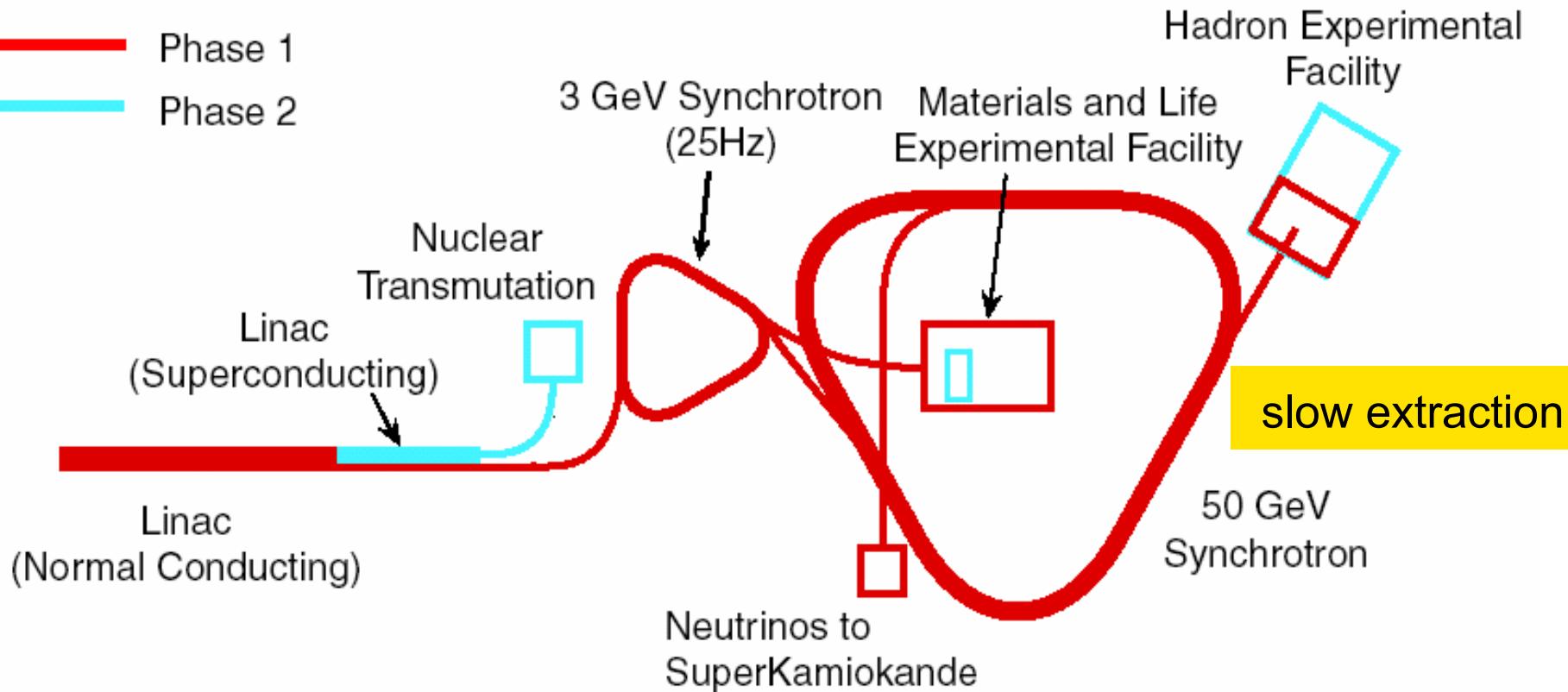
- Offset of the positron counter position
- Offset of the magnetic field
- Inefficiencies of MWPC, etc.

J-PARC Facility

KEK and JAERI



Phase 1 and Phase 2 of J-PARC



- *K*-decay experiments will be performed in the Hadron Experimental Facility using the slow-extracted beam

Beam parameters

■ Phase 1

- Day-1

Linac	180 MeV	30 mA	25Hz
RCS	3 GeV	0.6 MW	
MR	40 GeV	400 kW	

- Next Stage

Linac	400 MeV	50 mA	25Hz
RCS	3 GeV	1.0 MW	
MR	40 GeV	670 kW	

■ Phase 2

Linac	600 MeV	50 mA	50Hz
RCS	3 GeV	1.0 MW	
MR	50 GeV	750 kW	

(MR parameters are for the fast extraction beam operation)